TN NO. 64T-1

UNITED STATES NAVAL POSTGRADUATE SCHOOL

DEPARTMENT OF AERONAUTICS

TECHNICAL NOTE

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DATA REDUCTION FOR THE COMPRESSOR TEST RIG

by

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PREFACE

The main purpose of Tn No. 64T-1 is to serve as a guide to students using the Fortran cards for computer program "CMPRSOR" to reduce the data taken during a classroom test of the compressor test rig. This compressor test rig is described in USNPGS Technical Report No. 12.

To reduce data taken during a compressor test rig run, it is necessary only to follow directions on pages 7, 8 and 9 of this technical note. Appendix A will also help toward an understanding of the program and its use.

Appendix B gives the information necessary for slide rule calculations of efficiency data.

In content, TN No. 64T-1 is a compilation of information revelant to the compressor test rig not contained in USNPGS Technical Report No. 12.

1. <u>SYMBOLS</u>:

A	Amps.
S	Slip - RPM
T_F	Temperature - ^oF
T_c	Temperature - ^oC
V	Volts
W	Watts
W_1	Watts (Left Hand Watt meter)
W_2	Watts (Right Hand Watt meter)
W_L	Watts Loss

2. INTRODUCTION:

Technical Report No. 12 published in February 1955 by Professors Vavra and Gawain covers the construction and use of the compressor test rig and gives all information required for data reduction leading to values for flow and pressure coefficients φ and ψ. The derivation fo formulas for flow and pressure coefficients is also included in TR No. 12. The information given for slide-rule computation of flow and pressure coefficients φ and ψ is still pertinent; however, the computer program described and discussed in the above report applied to a computer no longer at the USNPGS.

The following supplements Report No. 12, in two respects: First, it shows the development of formulas for calculation of compressor efficiency by the use of a computer program and, second, it gives detailed information on the use of a Fortran program. This program is for the reduction of all data taken during a compressor test rig run.

3. COMPUTER PROGRAMMING OF MOTOR OUTPUT DATA:

Before 1956 the compressor test rig was operated without power input instrumentation. In 1956 the Westinghouse Company calibrated the compressor drive motor and supplied loss curves.

Net input to the compressor is equal to the input to the motor minus losses, since the compressor rotor is connected directly to the motor and the motor bearings carry all bearing loads. Input to the motor is the algebraic (since one wattmeter may have a negative reading) sum of readings from two wattmeters, the"two-wattmeter system" for 3-phase current. Total losses may be compiled by using the loss curves. Compressor efficiency, then, is the theoretical power required by the compressor divided by the net input to the compressor. A sample calculation (for slide-rule computation) of the motor output and curves from data supplied by the Westinghouse Company are given in Appendix B

In order to use the curves as part of a computer program it was necessary to reduce them to formulas Two of the curves are straight lines. Another curve has only three points. It was assumed that this curve is parabolic so the formula for the curve was set up as:

$$y = A + BX + CX^2$$

or, specifically:

$$\text{Watts Loss} = A + BX \text{ Volts} + CX \text{ (Volts)}^2$$

Substituting values at the three points given, three equations can be written from which the unknowns A, B, and C can be computed.

The remaining curve has seven data points. With the exception of one point, these points are on a parabolic curve determined by any three of the six points. The points were checked and found to lie on this theoretical curve to an accuracy greater than the accuracy to which the curve drawn through the points can be read.

For values above 12 amperes the constants of another parabolic curve were computed, using the 12 ampere point, the 14 ampere point and a point obtained by graphical interpolation between the 12 ampere point and the 14 ampere point.

The computer program calls for the computer to choose which formula to use, depending on whether the input is above or below 12 amperes. With Fortran a choice is called for by the "IF" statement.

A program for motor input and loss, and thus for compressor efficiency, was first written to supplement the original compressor test rig program written for the CDC 102. Reduction of efficiency data is now part of a complete data reduction program for the compressor written in Fortran.

For slide rule computations:

Efficiency = Theoretical Power of Compressor/Input to Compressor

Flow x Pressure x A Constant/Electrical Input - (Motor Losses + T_R)

"T_R" is the power loss due to the resisting torque of the water seal mechanism.

Input to the motor is measured by two wattmeters

$$W = W_1 + W_2'$$

At low power input the right hand wattmeter (W_2) may be negative; if this is indicated, two leads are reversed and the reading is recorded as negative.

For slide rule computations the meter readings must be multiplied by a factor to give true volt, ampere, and watt values. For use in compiling data for the Fortran program "CMPRSOR" meter readings are recorded exactly as read.

The ampere meter has multiple scales. The correct amperage is obtained by reading the second scale from the bottom and multiplying by 10. For slide rule computations an average istaken of the readings from the three meters.

Multiplying Factors

Amperes (Second Scale from Bottom)	Multiply by	10
Volts	" "	20
Watts	" "	40

For compiling motor losses reference may be made to the loss curves and sample calculations in Appendix A.

As an alternate method of computing motor losses for slide rule calculation of compressor efficiency the loss curve formulas may be used.

The combined friction, windage stray and core loss is a function of the voltage.

$$W_L = -210.0 + 0.8929\ V - 0.0001047\ V^2$$

Stator copper losses are a function of the amperage.

$$W_L = 2.73\ A^2 \text{ when } A < 12$$

$$W_L = 4484 - 783A + 33.0A^2$$
$$\text{when } A > 12$$

This loss is modified by a factor which is a function of motor winding temperature.

$$\text{Factor} = 0.904 + 0.00385\ T_c$$

Rotor copper losses are an indirect function of the slip. To get these losses the gross watts input minus the stator losses is multiplied by a factor which is a function of slip.

$$\text{Factor} = 0.000556 \times \text{Slip}$$

When the compressor is set up for taking rotor blade pressures there is an added loss, which is not a motor loss. This is the loss due to the resisting torque of the water seal mechanism. When rotor blade pressures are not taken this loss goes on the data card as zero.

For computing purposes the torque loss can be converted to equivalent watts.

W_L = Weight on Scales x Lever Arm x RPS x 2 π x A Constant

Lever Arm = 6" = 0.5'

RPS = RPM/60

$2\pi = 6.2832$

Constant = 1.356 (watts/ft-lbs/sec)

W_L = Wt. x RPM x 0.07095

4. DATA REDUCTION USING FORTRAN:

Program CMPRSOR was written to reduce data from the compressor test rig. A set of program cards is available.

With the facilities provided by the school it is necessary only to know how to fill out Fortran data forms so the data can be card-punched.

There are 21 items to be entered as data. The data cards must be in the following order:

First: The one card with 7 items of information.

Second: 1 to 4 cards with "RC(J)" values

Third: The two cards with the 12 data items required for flow and efficiency computations at the first flow rate.

Fourth: 1 to 4 cards with manometer board readings at the first flow rate.

Repeat "Third" and "Fourth" for "N" number of flow rates.

One line on the Fortran form equals one card, except that the Fortran form has only 12 spaces and the card has 80. Where all 80 spaces on a card are used, two lines on the Fortran form are required. For this program 70 spaces (for 7 items) can be on one line and the last data item can be entered on the first 8 spaces on the second line. Eighty card spaces are used for entering manometer readings and the "RC(J)" values.

All data entries are entered in 10 spaces per data entry item -- thus:

	1	2	3	4	5	6	7	8	9	10
BA = 30.06 is	3	0	.	0	6					
RPM = 1795 is	1	7	9	5	.					
PZ = 2.20846 is	2	.	2	0	8	4	6			

Floating point numbers may be placed anywhere in the assigned space. They are shown here in the first spaces. This system of palcement is the most convenient for the card punch operators. A decimal point

must always be included for floating point numbers.

The data is coded for ease of memory thus::

BA = barometer reading

EP = ε (epsilon)

Six items to be entered on the first card:

M = number of pressure readings for each flow rate.

N = number of flow rates.

NOTE: M and N are integers and must therefore be entered at the right-hand end of the space rpovided. IF M = 10 for 10 pressure readings, enter it as:

1	2	3	4	5	6	7	8	9	10
								1	0

There is no decimal point.

BA = barometric pressure in inches of mecury.

PZ = φ_0 --- See p. 74 of TR12 } Values depend on orifice diameter

EP = ε --- See p. 74 of TR12 }

TARE 1 = Tare of micromanometer for P_1 and Δp.

TARE 2 = Tare of micromanometer for A 42.

Next cards 1 to 4:

RC(J) Correction for centrifugal force of air in tubes for rotor pressures. Coded "Radius Correction". Find values on p. 75 of TR12. Enter "M" values. For pressures not on rotor blades enter RC(J) as zero. One blank card enters 8 zero values. (Blank cards used here should not be confused with the one blank card between program cards and data cards.)

For each flow value the following items are entered on two successive cards, the first 7 on the first card, the second 6 on the second card.

1. W1 = Watts reading on left-hand meter

   Note: The meter reading (A, V, W) are entered as read. The program multiplies by the correct factor.

2. W2 = Watts on right-hand meter. This may be negative.
3. A = Amperes. Enter average of 3 readings.
4. V = Voltmeter reading.

5. TW = Temperature of winding -- ^{o}C.

6. WT = Weight in pounds recorded on scales. This is for measurements of rotor pressures only. If other pressures enter WT as zero.

7. RPM = RPM

1. P1 = P_1'

2. T1 = Temperature in discharge pipe -- ^{o}F.

3. PA = ha = Atmospheric reading on manometer board in centimeters of water.

4. DP = $\Delta p'$ = Inches of water.

5. A42 = Plenum pressure reading at point A42. Read from micromanometer in inches of water.

6. TA = Temperature of air entering compressor -- ^{o}F.

"M" manometer readings are entered for "N" flow rates. PP(J) on computer program. Centimeters of water.

For each flow rate:

1 - 8	readings	- 1 card
9 - 16	readings	- 2 cards
17 - 24	readings	- 3 cards
25 - 32	readings	- 4 cards

The table of results is self-explanatory. The pressure (ψ) values are printed according to the order in which corresponding manometer readings, PP(J), were entered as data.

PROGRAM CMPRSOR

```
      PROGRAM CMPRSOR
      DIMENSION PSI (96), RC(96), PP(96)
       READ 100, M, N, BA, PZ, EP, TARE1, TARE 2
      READ 500, (RC(J), J = 1, M)
      BBA = BA* (13.55)
      DO 10  I = 1, N
      READ 500, W1, W2, A, V, TW, WT, RPM
      READ 500, P1, T1, PA, DP, A42, TA
      TTA = TA+459.4
      PP1 = P1-TARE 1 + BBA
      TT1 = T1 + 459.4
      DP = DP-TARE
      A2 = PZ*(1.-EP*DP/PP1)
      A3 = 1800./RPM * PP1/BBA * TTA/TT1
      A4 = SQRTF(TT1/520.*DP/PP1)
      PHI = A2 * A3 * A4
      OUT = (A42 +- TARE 2) * PHI * RPM
      V = V * 20.
      A = A * 10.
      WA = 40. * (W1 + W2)
      A2 = -210.+.8929 * V-.0001047 * V * V
      IF = (A-12.) 1000, 1000, 2000
1000  A3 = 2.73 * A * A
      GO = TO 3000
2000  A3 = 4484.-737. * A+33. * A * A
3000  A3 = A3 * (.904 + .00385 * TW)
      A4 = .000556 * (1800.-RPM) * (WA-A3)
      A5 = WT * RPM * .07095
      ETA = (OUT/(WA-(A2 + A3 + A4 + A5))) * 151.196
      READ 500, (PP(J),J=1,M)
      DO 20 J = 1, M
  20  PSI (J) = ((PA-PP(J)) * TTA (BA*RPM*RPM) * 64 10.2) + RC(J)
      WRITE OUTPUT TAPE 2,700, PHI
      WRITE OUTPUT TAPE 2,800, ETA
      WRITE OUTPUT TAPE 2,300
      WRITE OUTPUT TAPE 2,900
      WRITE OUTPUT TAPE 2,600, (PSI(J), J= 1,8)
      IF (M-8) 10, 10, 30
  30  WRITE OUTPUT TAPE 2,1100
      WRITE OUTPUT TAPE 2, 600, (PSI(J), J=9, 16)
      IF (M-16) 10, 10, 40
  40  WRITE OUTPUT TAPE 2,1200
      WRITE OUTPUT TAPE2,600,(PSI(J), J= 17,24)
      IF (M-24) 10, 10, 50
  50  WRITE OUTPUT TAPE 2, 1300
      WRITE OUTPUT TAPE 2, 600, (PSI(J), J= 25,32)
  10  CONTINUE
      END FILE 2
 100  FORMAT      (2I10, 5F10.5)
 300  FORMAT (27H  PSI (PRESSURE COEFFICIENT)//)
 500  FORMAT  (8F 10.5)
 600  FORMAT  (8F9.5)
 700  FORMAT  (////26H PHI (FLOW COEFFICIENT) = F6.5//)
 800  FORMAT  (20H ETA (EFFICIENCY) = F7.3,9H PER CENT//)
9000  FORMAT  (68H    1         2         3         4         5         6
   1     7         8)
```

PROGRAM CMPRSOR (Cont'd)

```
11000 FORMAT (69H        9         10         11         12         13       14
    1    15        16)
12000 FORMAT (69H       17         18         19         20         21       22
    1    23        24)
13000 FORMAT (69H       25         26         27         28         29       20
    1    31        32)
      END
      END
```

Program

Coded By

Checked By

Sample Data

Identification 73 80

Date

Page of

FORTRAN CODING FORM

CARD	FORTRAN STATEMENT (1–72)							
1	16	2	30.20	69.57	2.20846	.3213	.748	
2	.9025	.5169	.4538	.7065	.4927	.8542	.4566	
	.6731							
4	260.	20.	.5	123.	30.	5.	1795.	
5	12.79	69.57	95.75	4.079	12.948	68.0		
6	101.	112.5	113.	104.	105.5	116.5	109.	
	108.5							
7	112.5	110.	115.	112.5	118.	121.5	131.	
	140.							
8	261.	21.	.6	123.	31.	5.5	1795.	
9	13.03	68.5	94.82	4.22	11.732	67.0		
10	101.5	113.	113.5	104.5	106.	117.	109.5	
	140.5							
11	113.	110.5	115.5	113.	118.5	122.	131.5	
	140.5							

Card 1 applies to the whole run.
Card 2 is for the correction of centrifugal force, RC(J).
Card 3 is a blank card for RC(J) = o for the second 8 of the 16 pressure readings.
Card 4 and 5 are for flow and efficiency at the first flow rate.
Card 6 and 7 are pressure readings for the first flow rate.
Card 8 and 9 are for flow and efficiency at the second flow rate.
Card 10 and 11 are pressure readings at the second flow rate.

SAMPLE CALCULATION
Horsepower Output of Motor

Measured Test Data:

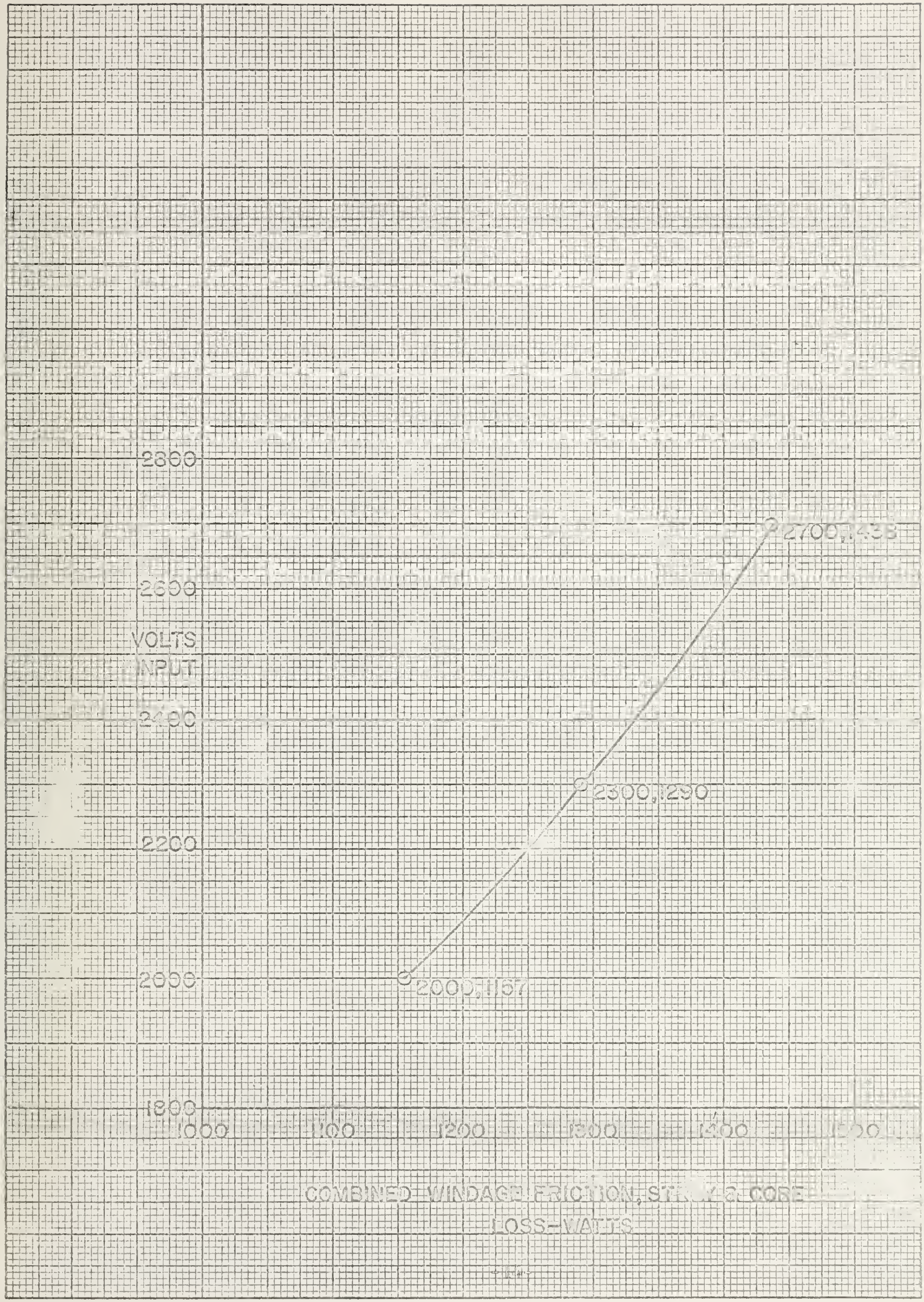
(1)	Input Voltage (ave. of 3 legs)	= 2300
(2)	Input Amperes (ave of 3 legs)	= 10
(3)	Input Watts	= 31760
(4)	Winding Temp. (°C)	= 20
(5)	RPM	= 1795

Motor Losses from Curves:

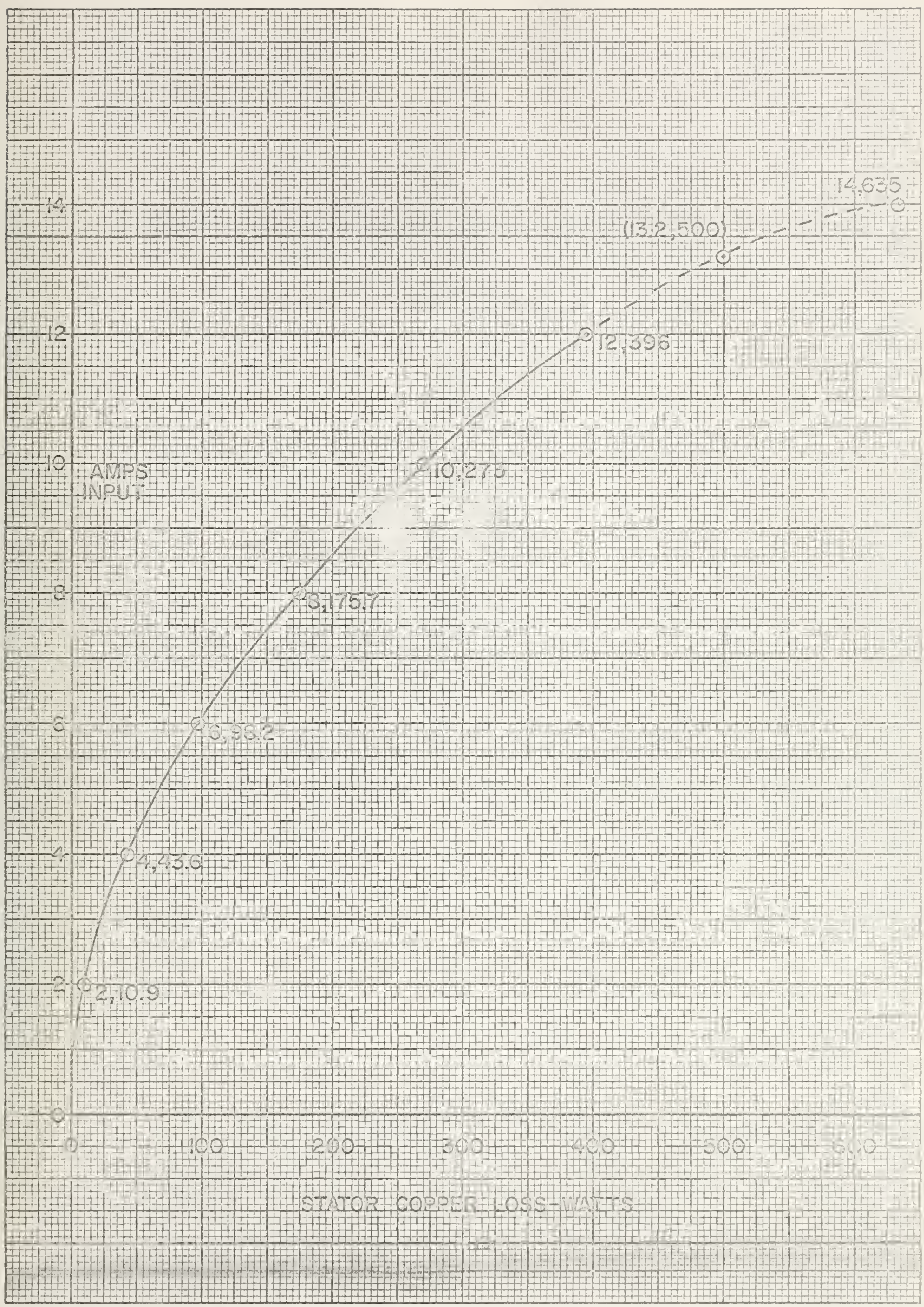
(6)	Combined Friction - Windage etc.	= 1290
(7)	Stator Copper Loss at 25°C = 273	
(8)	Temperature Correction Factor ≑ .981	
(9)	Stator Copper Loss at Winding Temp. 273 x .981	= 268
(10)	Slip Correction Factor .00834	
	Input Watts 31760	
	Minus Stator Copper Loss 268	
(11)	Input Factor 31492	
(12)	Rotor Copper Loss	
	Input Factor 3.492 (11) x Slip Corr. .00834 (10)	= 262
(13)	Total Motor Losses (6) + (9) + (12)	1820

Motor Output:

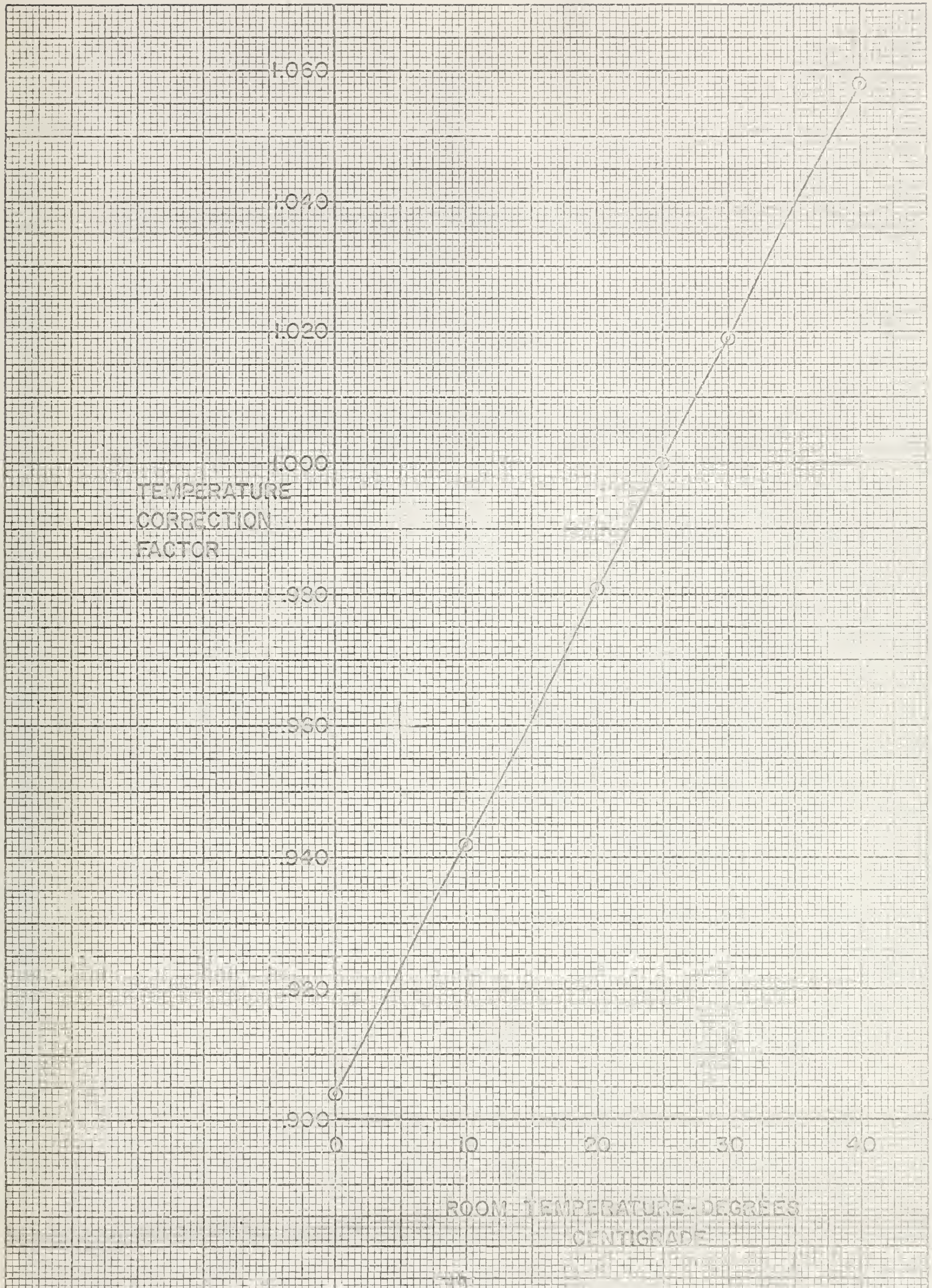
(14)	Input 31760 (3) - Losses 1820 (13)	= 29940
(15)	Watts Output (14) x .001341 = HP	= 40.2

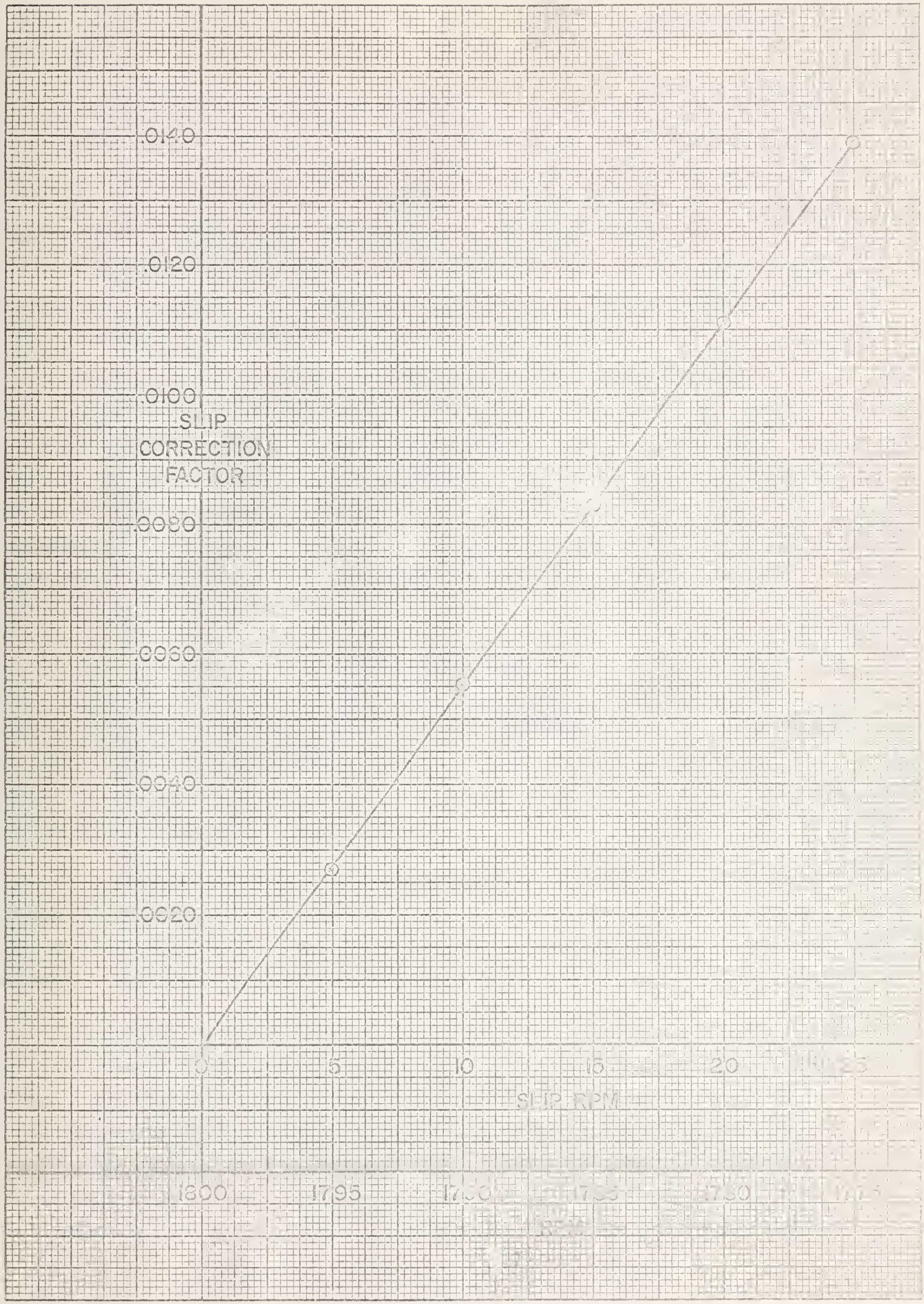


2800
2600
VOLTS
INPUT
2400
2200
2000
1800
1000
1100
1200
1300
1400
1500
2700,1438
2300,1290
2000,1157
COMBINED WINDAGE FRICTION, STRAY & CORE
LOSS-WATTS



14,635
(13.2,500)
12,396
10,275
AMPS
INPUT
8,175.7
6,98.2
4,43.6
2,10.9
0
2
4
6
8
10
12
14
0
100
200
300
400
500
600
STATOR COPPER LOSS-WATTS


1.060
1.040
1.020
1.000
TEMPERATURE
CORRECTION
FACTOR
.980
.960
.940
.920
.900
0
10
20
30
40
ROOM TEMPERATURE-DEGREES
CENTIGRADE



.0140
.0120
.0100
SLIP
CORRECTION
FACTOR
.0080
.0060
.0040
.0020
0
5
10
15
20
25
SLIP RPM
1800
1795
1780

Notes on the Use of the Compressor Test Rig for a laboratory test

1. The oil in the bearings should be checked when starting for the first time after, say, a week of no running. For shorter periods of time, loss of oil would be indicated by pools of oil underneath the motor. The bearings run cool so any bearing heat would indicate trouble. The motor should take from three to five minutes to come to a complete stop.

2 There has been no bearing trouble of any kind. However, there is an indication that bearing friction is a considerable motor loss. When the electrical instrumentation was first installed it was found that the input to the motor decreased during the first six hours of continuous running. One curve shows a decrease of 8.3% in the first four hours. This was analyzed as due to lowered bearing oil viscosity because of increased oil temperature. If possible the compressor should be run for two hours just before a laboratory class is held.

2. The motor must be started with the switches to the low-resistance shunts, that are across the instrument leads, closed. If they are left open the high starting amperage can ruin an instrument. There is also a switch on each of the meters that must be closed in order to read the meter. These switches may be locked open or they may be held closed for the time that the meter is being read.

3. The sharp-edge orifice in the discharge pipe used for flow measurements has an inside diameter of 13.535". If the orifice is, as before, taken out and the edge sharpened by a machining operation, the inside diameter must be measured accurately and the value recorded for flow measurement calculations.

4. There are several possibilities for pressure leaks in the lines from the orifice flange to the micromanometer: first, the connections at the orifice flanges may leak and, second, there is a possibility of pressure leaks at the quick-disconnect arrangement (the brass block and rubber cork rig) and, finally, the connections at, or even inside, the micromanometer, amp leak. For a rough check on the possibility of leaks it is noted that, at full flow, Δp is about 14" of water for 30^{o} conterflow setting of the inlet vanes and

about 10" for zero setting (vanes radial). This is for the usual 40^{o} setting of the vanes at the rotor discharge and for the 13.535" flow orifice, which is the one used. The 13.535" orifice was originally 13.500" I.D. The 11.5" and 15.5" orifices are not used.

5. For a test the following items must be at hand.

A thermometer

Two micromanometers

Four clip boards

Blank data sheets. There are kept in Room 123, Bldg. 234.

RPM counter

USNPGS Technical Report No. 12

Several copies of this publication

Ozalid print of cross-section of test rig, drawing No. 665.

Ozalid print of cross-section of water seal mechanism, drawing No. 542B.

One micromanometer is used for flow measurement.

One micromanometer is connected to pressure tap A42 for the plenum pressure.

Pressure lines will be connected to a 40-tube manometer board as outlined by the professor conducting the class.

The ozalid prints are to aid the professor holding the class in explaining the rig and its use.

6. When taking rotor vane pressures great care must be taken in entering the water used for isloating the pressure chambers. If the water is let in at too high a head some of it may get into one or more ot the small-diameter pressure lines leading to the tap locations. When this happens a reading at the tap affected cannot be taken until the rotor is removed and the line cleared. The can that is raised to force water into the water seal mechanism is raised slowly two or three feet above the center-line of the compressor and lowered as soon as all chambers are isolated. A manometer board pressure reading not the same as that from either of the two adjacent isolation chamber readings, and constant, is an indication that sufficient water has entered to isolate the chamber connected to that particular tube. More than sufficient water may cause water to be trapped in the pressure lines from the rotor tap locations.

ACCESSION NO.

U-90,286

Compressor
Test
Rig
FORTRAN
Efficiency
Calculation
Computer
Data
Reduction
Flow
Pressure
Coefficients